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Published in:
Proceedings of EuroCorr 2014

Publication date:
2014

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Citation (APA):
Jellesen, M. S., Verdingovas, V., Conseil, H., Piotrowska, K., & Ambat, R. (2014). Corrosion in electronics: Overview of failures and countermeasures. In *Proceedings of EuroCorr 2014*

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Corrosion in electronics: Overview of failures and countermeasures

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Summary

Many field failure returns of electronics are marked as “no failure found”, yet numerous of these failures are likely due to corrosion, since corrosion related failures are not easily detected during subsequent failure analysis. In some cases failures are intermittent and occur because of service life conditions (humidity and contamination) where water film formation on the printed circuit board assembly (PCBA) leads to leakage currents resulting in wrong output signal of the electronic device. If the leakage current itself will not result in malfunctioning of the electronics, the formed water film and potential bias of the PCBA will eventually lead to failure caused by more easy recognisable corrosion. Typical corrosion failure types seen in electronics are galvanic corrosion, electrochemical migration, and other types of bias induced corrosion.

This paper describes the most commonly used metals and alloys in electronic devices including aluminium, gold, copper, silver, tin, lead and their alloys. Galvanic series performed in a flux solution is presented together with examples of galvanic corrosion causing failure of electronics. Failures that find root cause in the manufacturing process are described in details, e.g. flux activator related failures. Failures caused by service life conditions with high humidity and sulphur containing gaseous environments are also described. Finally it is described how the architecture of the PCBA (the placement of components) will affect its corrosion reliability. Infrared camera imaging is used to show the thermal distribution of the PCBA during power on periods and can reveal local cold spots on the PCBA being prone to condensation and corrosion.

1 Introduction

Practically all metallic materials on a PCBA are susceptible to corrosion under biased conditions in humid service environments, especially if aggressive ions are present. Most often, metallic materials used for PCBA applications are not selected with corrosion reliability as a major criterion, but primarily for their electrical, electronic, magnetic, or mechanical properties. In high performance products, the PCBA is coated or shielded from external environment by encapsulation, but corrosion can still take place and cause the electronic device to fail if the service environment is severe. In practice, failed electronics used in industrial applications needs replacement and the loss of production time can be very costly or even pose safety hazards. The expenses incurred for this often greatly exceeds the cost of the failed component itself.

2 Water film formation and leakage current failures

Both process- and user related contamination will influence the corrosion reliability of a PCBA and the electronic device as a whole. An important process related contamination is solder flux residues which can act as a corrosion promoter in humid atmosphere due to the presence of ionic substances and a resin component.

One example of an electronic device failure due to solder flux residue is shown in figure 1. Tactile switches are mounted on the PCBA by hand soldering process due to the presence of a large copper layer inside the PCB laminate under the switches. Due to the high heat capacity of copper, heat will be taken away during the automated soldering process resulting in a weak solder joint. Therefore, as an alternative, hand soldering is performed using a standard lead containing solder assisted by excessive use of “No-clean” hand soldering flux. The purpose of the flux is to act as a wetting agent and surface activator during the soldering process. Although the idea of using “no-clean” flux is to leave minimal residue after soldering, in practice large amounts of residues are left on the PCB surface, depending on the skills of the technical personnel performing the soldering work.¹

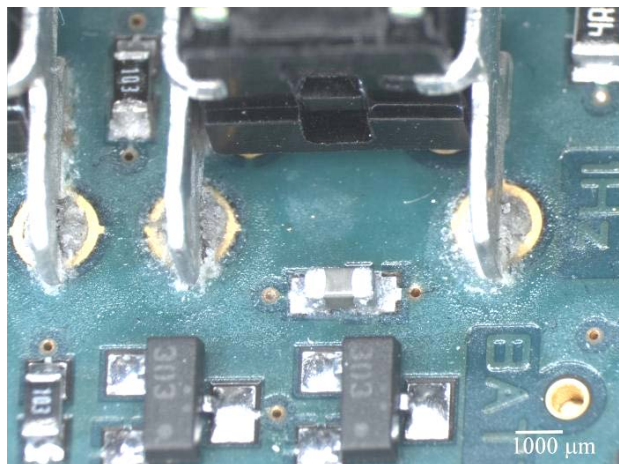


Figure 1 A micro tactile switch mounted on a PCBA with excessive amounts of remains of no-clean flux. Flux residues are visible on laminate as well as on surrounding components.

The “No-clean” hand solder flux systems often contain carboxylic acid- or/and halogenide (activator) in order to facilitate the chemical reactions that remove oxides on the metal surface. Resin is added to prevent re-oxidation of the cleaned metal. The effect of temperature on the degradation of flux residue showed that a temperature above 250 °C is needed for complete decomposition of carboxylic acid components in a no-clean wave solder flux.² When hand soldering is used, a temperature of 350 °C for a few seconds is advised, but this temperature is very local and the regions close by will only experience much lower temperatures. This causes a risk of large amounts of unreacted flux remaining on the PCBA, which will influence the long term reliability of the electronic component/product during application.

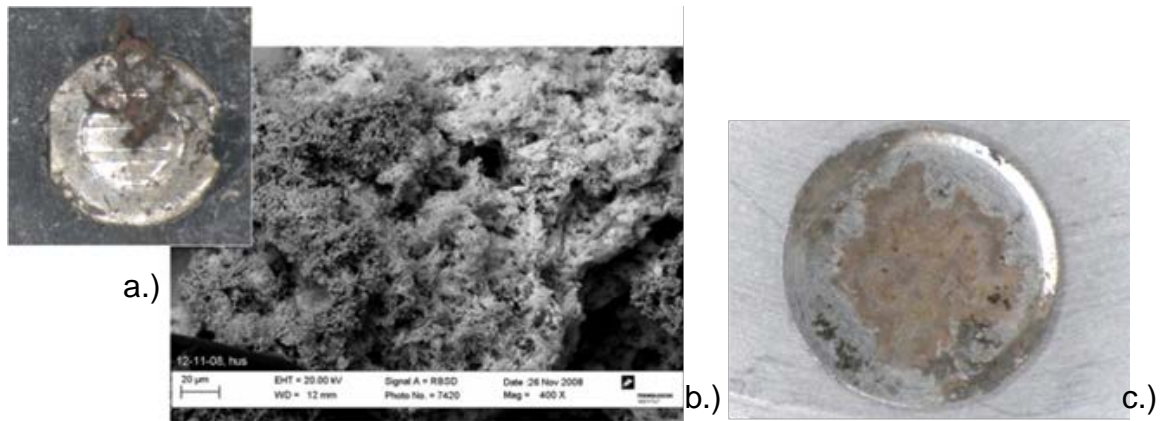


Figure 2 Pictures of a.) failed switch center terminal, b.) SEM micrograph of corrosion products and c.) backside dome showing corrosion of the silver layer.

Failed PCBA's were sent for analysis after use in atmospheric conditions with high humidity and temperature cycles (day and night shifts). The tactile switches gave 2 types of failure; one failure mode was seen as the failed PCBA's were returned at an early service life stage where it was observed that the resetting action of the switch failed due to high ohmic resistance as a result of substantial amount of resin part of flux residue inside the switch acting as a dielectric barrier. The other failure mode is due to severe corrosion resulting in resetting due to short circuiting inside the switch. The corrosion of tin and silver inside the switch was accelerated by the intrusion of active flux activator into the switch house, caused by the low surface tension of the flux.

An example of a field failure return showing white residues is given in figure 3. The white coloration can be due to various reactions of the flux residue rosin e.g. oxidation or hydration.



Figure 3 Field failure returned PCBA showing white residues near integrated circuit chip component.

As such the white residues are not necessarily harmful for the electronic circuit, but if active acid residues are present it can cause unwanted leakage currents and corrosion. A Fourier transformation infrared spectroscopy (FTIR) analysis of a reference PCB laminate compared with the white residues shows correlation to succinic acid indicating that for this field failure there are active acid left in the residues. It is likely that humidity have reacted with the resin part of the reflow flux residue causing a release of the activator part.

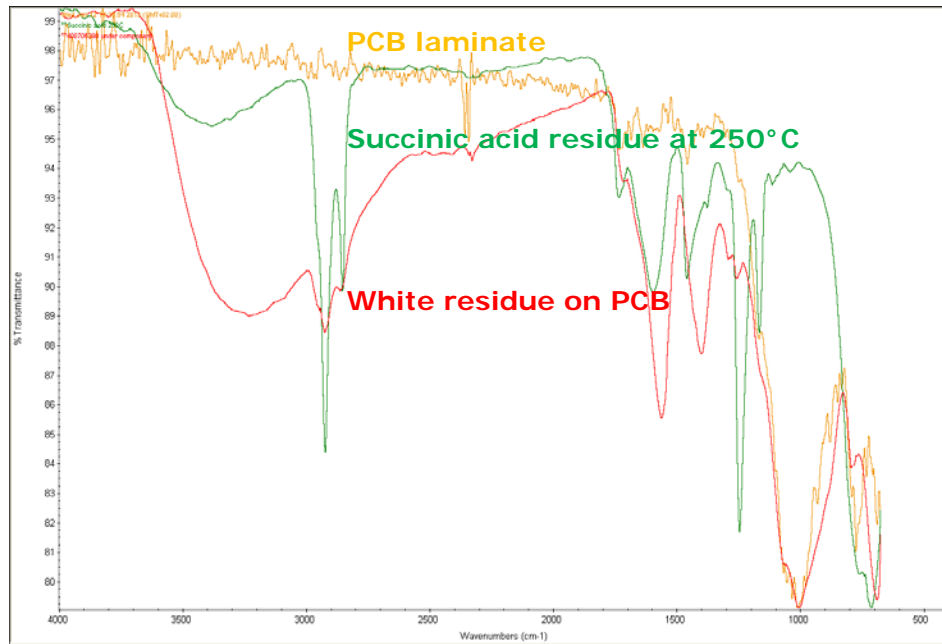


Figure 4 Fourier transformation infrared spectroscopy analysis of white residues shown in figure 3. The peaks seen for spectrum made in white residues area differ from spectrum made in a reference area on the same PCBA and these peaks corresponds to peaks found for succinic acid.

Leakage current and corrosion is more likely to occur if active acid is present in an area on the PCBA that is populated with components having closely distanced biased lines e.g. integrated circuits as is the case shown in figure 3.

During change to lead free soldering a product was humidity tested in same manner as when the PCBA was lead containing soldered. Despite the soldermask not being intended to be used as an electrical insulator and water barrier for the PCBA it fulfilled this for the lead soldered PCBA. With the higher soldering temperature when going to lead free, more pinholes at the edges were seen in the soldermask (figure 5).

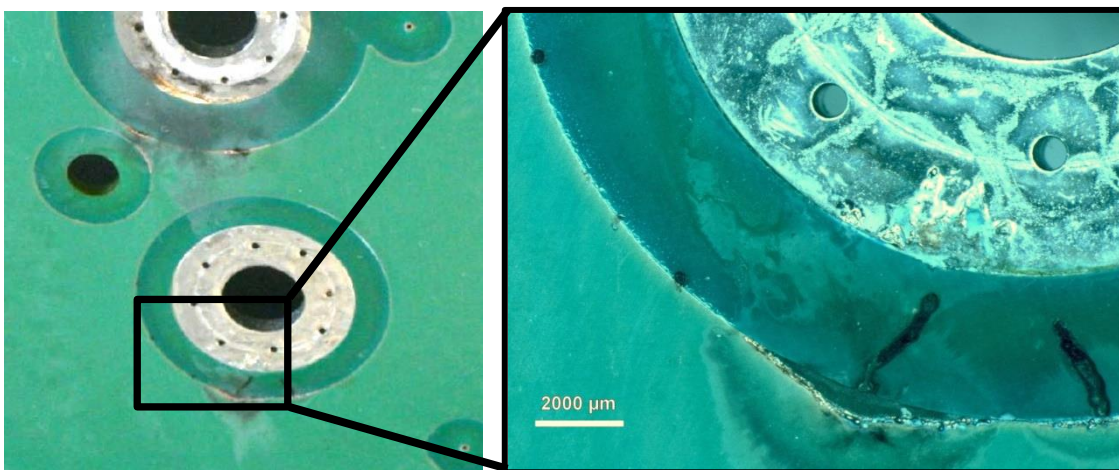


Figure 5 Condensation test of wave solder lead free high power PCBA showing electrical short circuiting due to solder mask pin holes. The black spots seen are due to corrosion of Cu under the pin holes in the solder mask.

High humidity and varying temperatures caused condensation and flash over between 400V biased points on the PCBA, one of them being the bare copper under a pinhole in solder mask.

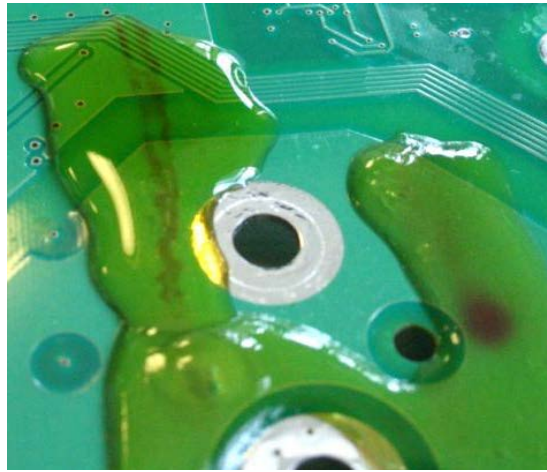


Figure 6 Residues Rat testing of high power PCBA indicating droplet formation during condensation test and red coloration due to active acid residues left on the PCBA surface.

Residues rat gel testing (figure 6) indicated flux and droplet formation on the PCBA surface so overall the combined effects of high bias, high humidity and pin holes in solder mask caused leakage current and finally short circuiting. One possible countermeasure could be to make a double solder mask in order to minimizing risk of pin holes, yet solder mask itself cannot be expected as a reliable water barrier layer, thus also measures for encapsulation in order to minimize the risk of condensation is needed.

3 Galvanic corrosion

Generally, the materials for electronics are not selected by considering corrosion behavior as an important criteria or parameter. There are numerous examples on PCBAs where dissimilar metal/alloy combinations are present. For example, during electroless nickel immersion gold (ENIG) surface finish, immersion Au coating is made on the Ni barrier layer. If low thickness of the Au layer, the surface becomes porous and the Ni layer is exposed through the porous Au layer, hence corrosion of Ni is accelerated due to the dissimilar corrosion potential of the materials. In such cases, a slightly thicker layer of Au coating or carefully avoiding the porous surface would greatly reduce corrosion failures.

Another example of dissimilar metal contact is Al bond pad corrosion (figure 7), which occurs due to the high electrochemical potential difference between Al and Au.

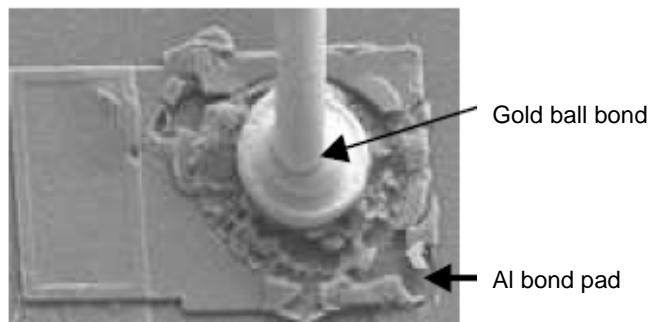


Figure 7 Corrosion of Al bond pad in contact with Au ball bond

The electrochemical potential of all metals/alloys are listed in figure 8 with decreasing nobility from top to bottom and divided into bulk materials, and similar or different metals/alloys as coatings on the PCBA. Among the bulk metals/alloys, tin and SnAgCu solder (SAC) is found to be the most active followed by nickel in both solutions, while Au, Ag and Cu are more noble. For all metals/alloys, the electrochemical potential in 10% sweat solution is more active compared to that in the flux solution. This is understandable as the sweat solutions has higher conductivity and contain chloride ions, thus increasing the aggressivity of the solution. Among the metals/alloys coatings on the PCBA, those coatings that have major element similar to bulk materials follow similar trend with only a slight difference in potential indicating the potential of bulk metals/alloys can be used very well in considering the galvanic coupling on the PCBA. Similar to bulk metals/alloys, coated materials also showed more active potentials in the sweat solution compared to the flux solution. ³

	10 % Flux solution		10 % Sweat solution	
	Materials	Electrochemical potential (mV)	Materials	Electrochemical potential (mV)
Bulk	Au	+186	Au	+156
	Ag	+147	Ag	+58
	316L SS	+146	316L SS	+46
	Cu	+50	Cu	-26
	Ni	-110	Ni	-171
	SAC solder	-391	Tin	-480
	Tin	-438	SAC solder	-502
	Al	-532	Al	-668
Coatings on PCBA	Ag-Roll bonded	+167	Au-Immersion coated	+156
	Au-Immersion coated	+115	Ag-Roll bonded	+58
	Mobile dome-Steel-AISI 202	+102	Mobile dome-Steel-AISI 202	+18
	Cu -electroplated	+39	Cu -electroplated	-31
	Ni-Electroless coating	-241	Ni-Electroless coating	-287
	Sn- surface finish	-329	Sn- surface finish	-462
	SAC solder-HASL	-418	SAC solder-HASL	-474
	Al-Sputter coated	-502	Al-Sputter coated	-583

Figure 8 Electrochemical potential of PCBA materials. ³

Many times, a proper choice of material combinations or avoiding galvanic couple formation by eliminating porosity in multimetallic layers can improve the corrosion reliability of different parts of a PCBA. In the case of switches that have terminals made of steel that comes in contact with a silver plated dome the corrosion resistance of the steel determines the probability of galvanic corrosion occurring. If, steel of high quality like 316L stainless steel is used, the corrosion potential of such stainless steel and silver is similar, which leads to lower risk of galvanic corrosion. Hence, the selection of PCBA metallic materials or combinations with consideration of electrochemical and corrosion behaviour whenever possible is an important step towards building reliable PCBA. The standard tables and charts with electrochemical and galvanic potentials of PCBA metals/alloys should be available to the designers in order to understand how various designs can perform against corrosion.

4 Failures caused by severe service life conditions

The exposure of electronics to environments where temperature, humidity and atmospheric pollutants such as chlorides, NO_x, SO_x, and hydrogen sulphide (H₂S), which are not controlled, can result in atmospheric corrosion of the metallic components on the PCBA. In order to minimize the risk of corrosion failure, it is important to be aware of corrosion risk during the design stage, reliability evaluations and qualifications, assembly processes, storage, shipping, and in the final use of the microelectronic devices. ^{4,5}

Immersion silver is being used to replace hot air solder levelling as the surface finish on PCBs. If service life conditions contain H₂S or SO₂ gas such surface finishes can suffer from sulphur corrosion if humidity levels are high. Failures can occur in as little as a few weeks in industries such as rubber manufacturing, water treatment, paper mills or fertilizer production, among others. ⁶

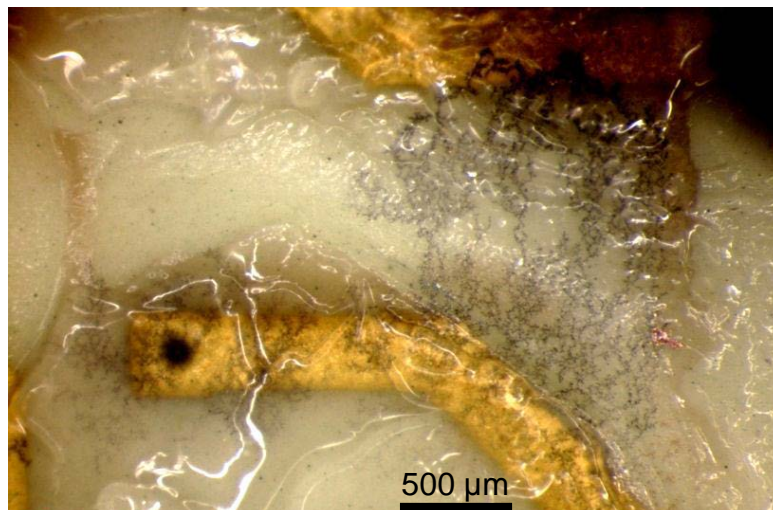


Figure 9 Field failure return showing silver dendrites formed between conducting lines under conformal coating.

In a field failure return from a pig farm sulfide corrosion of silver surfaces was observed on a hybrid due to permeation of corrosive sulphur gasses through the silicone coating (figure 10).

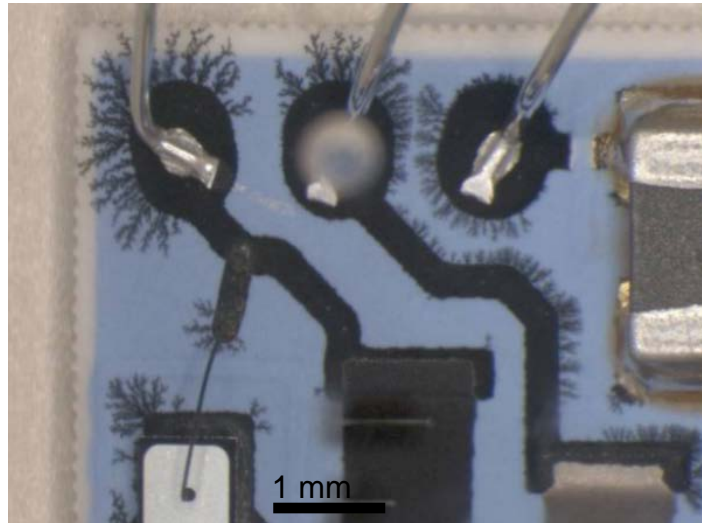


Figure 10 Severe sulphide corrosion of silver lines in a power module after use in pig farm environment containing sulphur gases. The power module was covered with silicone coating through which sulphur gas permeated.⁷

Three types of corrosion features were observed namely: uniform distribution of silver sulfide, dendritic growth, and creep corrosion of silver on gold wires.⁸

A study of silver corrosion at indoor conditions in an electronics production site dedicated to assembly and functional testing of microelectronic devices has been reported.⁹ Silver plated copper lead frames showed sulphur corrosion due to presence of hydrogen sulphide because of vapour emissions from a nearby geothermal power plant. The concentration of H_2S in the tested electronics plant atmosphere was 0.9 ppm and in some areas of the assembly process reaching 1.5 ppm, due to the operation of ovens used for curing epoxy resins as part of the manufacturing process. Temperature was reported to vary between 19-27 °C and relative humidity from 32 to 64 % RH. After 60 days silver coupons showed clear color change into royal blue coloration in the centre surrounded by purple at the edges.⁹

Countermeasures against sulphur corrosion involves the control of several atmospheric factors (wherever possible), including lowering of air humidity and temperature and the level of contaminants in order to avoid silver corrosion and improve the reliability of electronic products.

5 Architecture of a PCBA and climatic reliability

Temperature variation on a PCBA plays a major role in its reliability, especially when exposed to outside application environments. An Infrared (IR) image of a circuit board under biased condition is shown in figure 11. The temperature of the board varies from 25°C to 50°C. There are certain electronic components with high resistance, which dissipate heat more than other components like transistors or capacitors.

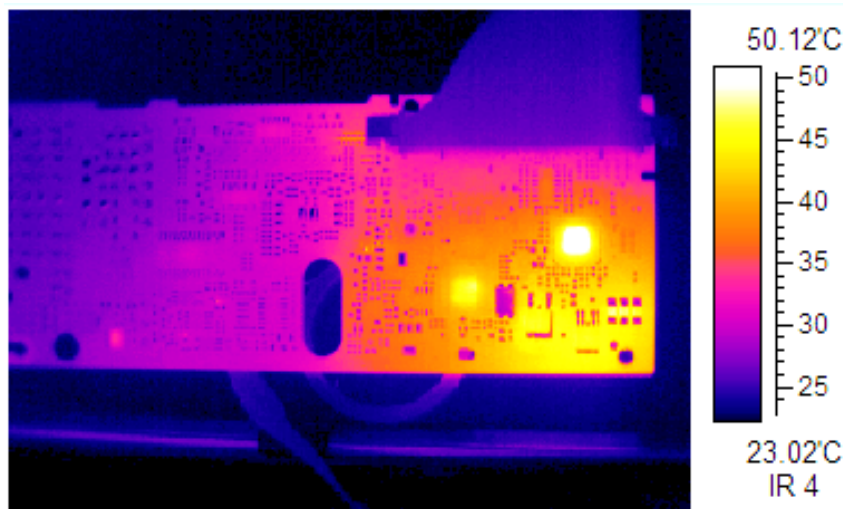


Figure 11 Thermal image of a PCBA under biased condition showing variation in temperature as 50°C maximum to 25°C minimum.

From a corrosion point of view, the local temperature variation can change the way humidity interact with the PCBA surface. There is a significant possibility for more interaction of humidity (water layer formation, slow drying etc.) in the colder part of the boards depending on the outside temperature and level of humidity when a PCBA is exposed to the humid environment. Thus, maintaining uniform heat distribution throughout the board or placing the corrosion sensitive components near the hot zone of the board protects the circuit from condensation effects.

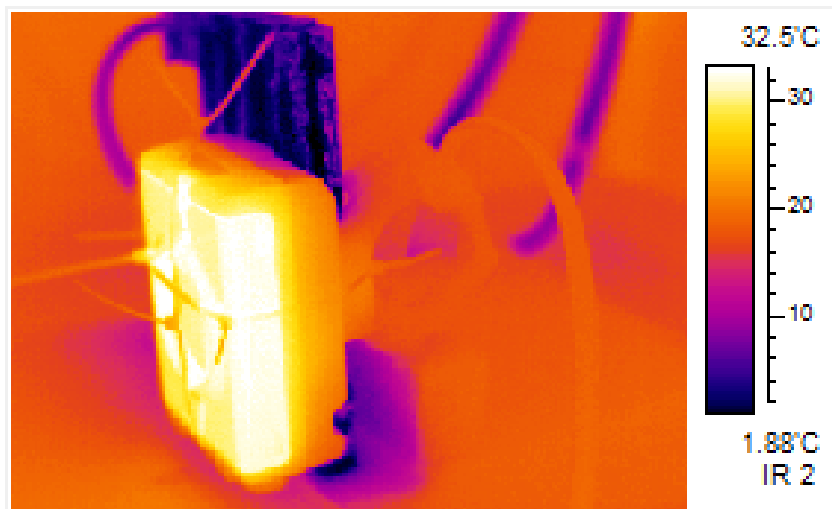


Figure 12 Thermal image of a biased electronic product exposed to condensation test in humid environment. The electronic encapsulation is placed on a water cooled metal block in order to promote condensation.

Another type of electronic product was investigated in a condensation test using thermal infrared camera (figure 12). For this product the self-heating when biased is distributed homogeneously and it was not possible to create condensation on the PCBA surface inside the encapsulation as long as the product is biased.

Summary

Electronic devices can fail due to a number of failure modes depending on inherent factors related to PCBA materials, design, and cleanliness under exposure to humidity and other gaseous conditions. Some failures can be avoided by simple remedial measures such as changes in materials, slight change in PCBA design, and optimal PCBA cleanliness.

Acknowledgements

The research reported here has been conducted as part of the CELCORR/CreCon consortium (www.celcorr.com). Authors would like to acknowledge the consortium partners for funding support and all the help received during the program run.

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